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The goals of this grant were to understand the physics of flows generated by currents passing over small topographic features and to quantify and parameterize, if possible, the mixing these flows produce.

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Flow over difficult bathymetry: processes and parameterizations

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LONG-TERM GOALS

To understand the physics of flows generated by currents passing over small topographic features and to quantify, and parameterize if possible, the mixing these flows produce.

OBJECTIVES

- To synthesize emerging measurements and numerical simulations of flow and mixing over rough topography to assess their global significance.
- To understand the physics controlling exchanges of momentum, heat, and salt between boundary layers over continental slopes and the ocean's interior.
- To use laboratory and numerical results to design experiments illuminating crucial aspects of flow and mixing over rough topography.

APPROACH

Because the university gave us no break on overhead, the SECNAV funds were not enough to mount significant field experiments in the open ocean. Instead, we 1) worked in inland waters where useful measurements can be done more cheaply, and 2) leveraged the SECNAV funds by seeking additional support for related efforts. In addition, some of the work developed in ways not forseen when we wrote the proposal and dealt with other aspects of mixing and internal waves in the open ocean.

Gregg also attempted to establish better links between the academic oceanographic community and the Naval Oceanographic Office. He went to Bay St. Louis and met with the CO and technical director of the facility there. Both seemed enthusiastic and said they

would follow up and contact him to develop such a group, but nothing happened. Back door inquiry revealed that NAVO was not in fact interested in closer contacts.

WORK COMPLETED AND MAJOR RESULTS

Because this is the final report and most of the work was described in our annual reports, rather than repeat those descriptions we here show how the many publications from this project are related.

Not shown in the publications, but two of the major accomplishments from the grant are developoment of two excellent young scientists with postdocs supported by the Chair and Scholar. Gregg supported Matthew Alford with a postdoc, and Matthew is now a permanent staff member of the Ocean Physics Department and an affiliate assistant professor in the School of Oceanography at UW. He is well supported by ONR, including a Presidential Young Investigator grant. MacCready supported two postdocs, Geno Pawlak and Kate Edwards. Pawlak is now a tenure-track assistant professor in the Department of Ocean Engineering of the University of Hawaii, Manoa campus, and Edwards is a staff scientist at the Applied Physics Laboratory of the University of Washington. In addition, Gregg supported three graduate students, Jody Klymak, John Mickett, and Glenn Carter, and MacCready supported two, Martin and McCabe.

Hydraulically-controlled flows. Gregg began working on hydraulically-controlled flows during the ONR-sponsored Gibraltar Experiment (1985-86) and found himself involved again after a survey of turbulence in Puget Sound funded by Washington State Sea Grant. Because these flow produce some of the strongest turbulence observed in the ocean, ONR funded work in the Bosphorus (1994) and the Knight Inlet Experiment (1995). Some of Gregg's share of the analyses of the latter two was supported with the Chair and led to *Özsoy et al.* [1998], *Gregg et al.* [1999], *Gregg and Özsoy* [1999], *Özsoy et al.* [2000], *Özsoy et al.* [2001], and *Gregg and Özsoy* [2002] for the Bophorus and *Klymak and Gregg* [2001], *Klymak and Gregg* [2003a], and *Klymak and Gregg* [2003b] for Knight Inlet. Jody Klymak was a graduate student with Gregg and is now doing a postdoc at Oregon State with Jim Moum.

Major results of the Bosphorus analysis include

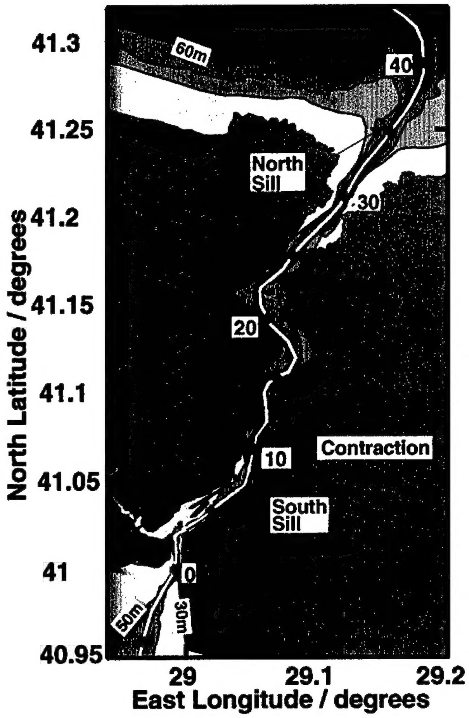
- Flow through the strait seems to be regulated by an hydraulic control at South Sill, the 35-m-deep cross-channel ridge near the southern entrance (Fig. 1).

- This control differs from others previously observed in having major portions of the exchange flow crossing the sill on opposite sides of the channel.

- The height of the interface seems to be regulated by an hydraulic control across North Sill which is in the preBosphorus Channel just north of the strait (Fig. 1). Nearly all of the dense water exiting the Bosphorus is confined within this channel .

- Although a third hydraulic control was predicted in or near the Contraction in the strait (Fig. 1), we failed to find it. The composite Froude number was so far from

critical that we believe the flow to be the first example reported of viscous control, similar to that predicted theoretically by *Hogg et al.* [2001].



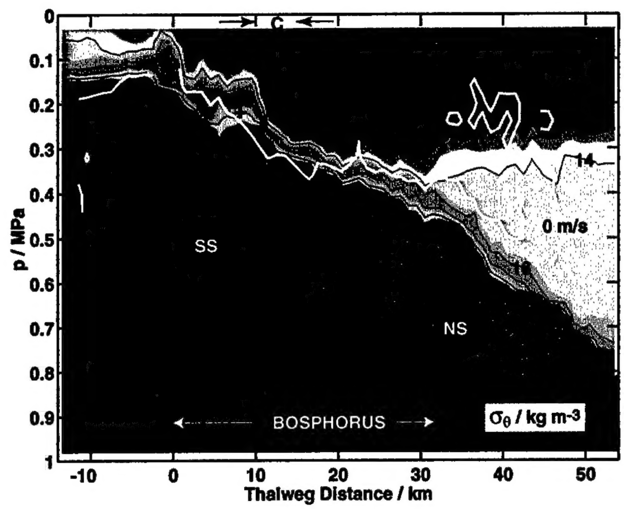


Figure 1: Major features of the Bosphorus are shown on the left, and the average density section on the right illustrates the exchange flow. Distances, in red on the left, are referenced to the southern entrance.

Major results from the Knight Inlet work are

- Flow downstream of the sill is strongly three-dimensional except for a narrow region that is near the center of the channel over the sill (Fig. 2. Previously flow at Knight Inlet and other sills was assumed to be uniform across the channel.

- The large-scale response of the barotropic tide to the sill, known as upstream influence, is very important to flow structure at the crest. At Knight Inlet this includes effects resulting from an average density gradient across the sill owing to the pool of dense ocean water blocked on the seaward side.

- Although intense, turbulence measured near the sill is too weak to account for the amount of energy lost by the barotropic tide over the sill.

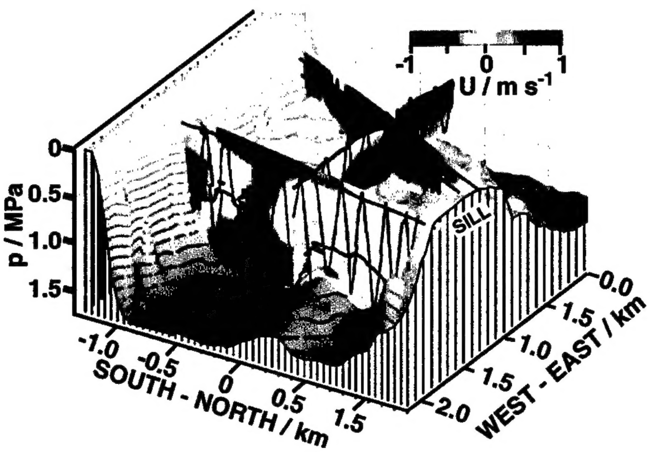


Figure 2: Isometric view of flood tide over the Knight Inlet sill [*Klymak and Gregg*, 2001]. Landward flow is positive. Although flow over the sill crest is nearly barotropic, i.e. constant with depth, downstream the flooding water splits into a surface jet, a bottom density current, and a narrow column linking the two between two vortices flowing seaward. Bottom irregularities direct this structure away from the channel centerline and toward the southern shore.

Drag and vorticity induced by flows along slopes.

Low-latitude mixing. Funds for the Chair enabled Gregg to synthesize all of the data taken with the Multi-Scale Profiler (MSP), which with constructed with ONR funds in the early eighties, to examine the latitude dependence of turbulent dissipation rates, ϵ, predicted by *McComas and Müller* [1981] and *Henyey et al.* [1986]. Their predictions can be written as the product of one term depending on stratification and the local shear and variances of internal waves,

$$\epsilon = \epsilon(N^2, Shear^2, Strain^2) L(latitude) \ . \qquad (1)$$

The second term depends weakly on stratification and principally on latitude. It arises from 1) concentration of internal wave shear at near-inertial frequencies and 2) dependence of the vertical-to-horizontal aspect ratio of internal waves on frequency. Essentially, the rate of interaction that moves energy from large to small scales and ultimate breaking decreases with latitude as the near-inertial frequency goes to zero.

Comparison between predictions and measurements (Fig. 3) is better than expected owing to approximations made in the theoretical derivations. Close to the equator, this effect

reduces ϵ to about 1/30 of the value that would result from the same internal wave parameters at mid-latitude. Owing to the weak dissipations, internal wave shears sometimes build up to very large levels at low latitude before reaching a balance with dissipation.

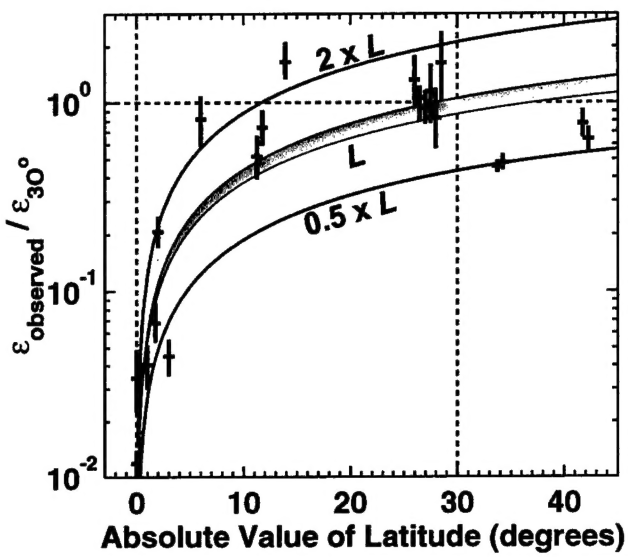


Figure 3: Comparison of measured ϵs corrected for the first term in 1 with the theoretical prediction of the second term [*Gregg et al.*, 2003]. Ensemble averages of the corrected dissipation rates are marked by crossbars on the 95% confidence limits of the measurements. Shading shows variability in the latitude dependence resulting from differences in measured N^2, and the $2 \times L$ and $0.5 times L$ lines show the 2-fold uncertainity expected for the predictions.

Wind inputs to the internal wave field.

As Gregg's postdoc, Alford published four papers with total or partial SECNAV support. The first, [*Alford et al.*, 1999], reported on the first (and only) direct microstructure measurements in the Indonesian throughflow. Measured mixing rates were well below those implied by large-scale budgets; however, 3/4 of the mixing that was observed as causatively attributed to an energetic near-inertial wave, which appeared to have been generated by strong monsoon winds, which had ended some weeks before the cruise. This was written up in *Alford and Gregg* [2001]. An interesting kinematic consequence of tidal heaving of the near-inertial shear layers was that the tidal peaks were 'split.' This proved to be a simple case of 'fine-structure contamination,' which Alford wrote up in JPO [*Alford*, 2001]. Finally, the Banda Sea wind-generated near-inertial waves inspired an extension to the globe using National Center for Environmental Prediction (NCEP) winds [*Alford*, 2001]. This study suggested that wind-generated near-inertial waves may be as important a source of energy for ocean mixing as the tides, and prompted a series of papers on the topic funded by Alford's

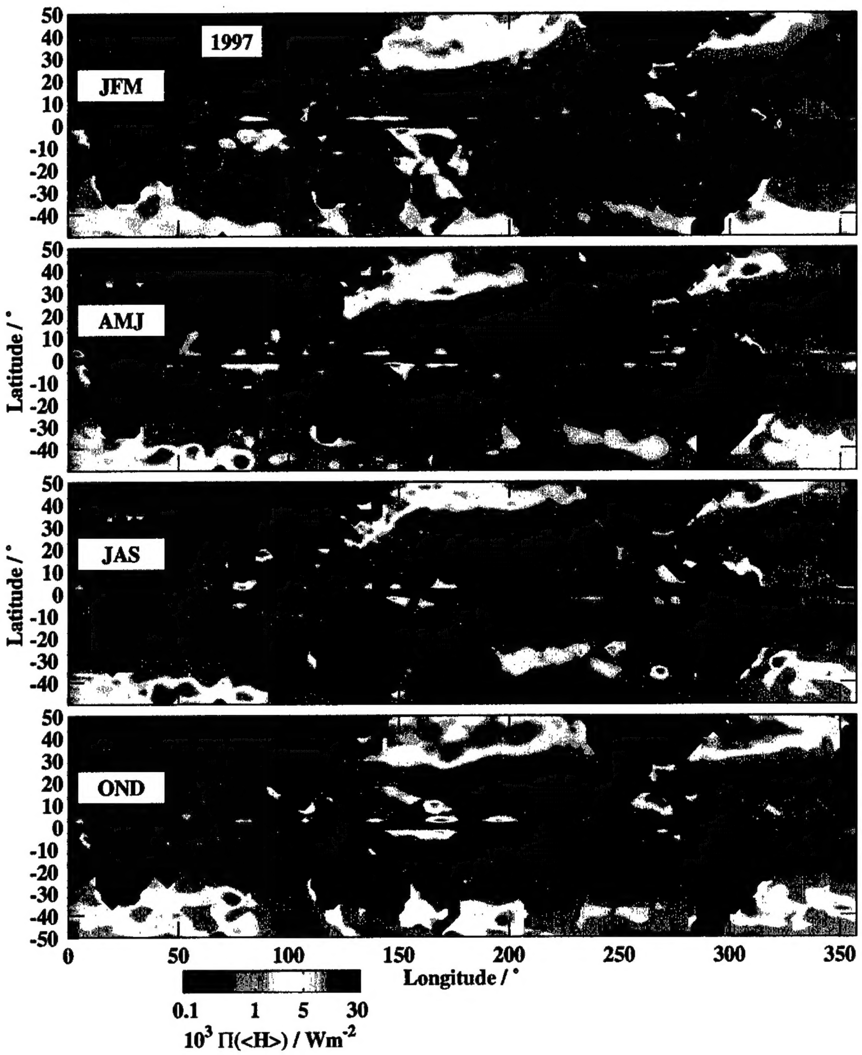


Figure 4: Calculated input of energy to near-inertial internal waves by the wind *Alford* [2003].

YIP award , one of which is *Alford* [2003].

Flow over rough topography

Laboratory experiments were conducted to determine how residual flows near coastlines might be affected by tidal flow past multiple headlands [*Pawlak and MacCready*, 2002]. The striking result was that the residual transport could be directed toward the coast if the eddies were sufficiently long-lived, counter to the usual result that headlands direct water offshore. To test these ideas observationally, headland eddy lifetimes at Three Tree Point, WA (Fig. 5), were quantified observationally in Pawlak et. al (in press). These eddies were found to decay after only 9 hours, a much shorter time than predicted by bottom friction. This rapid decay appears to be caused by the interaction of baroclinicity with vortex tilt.

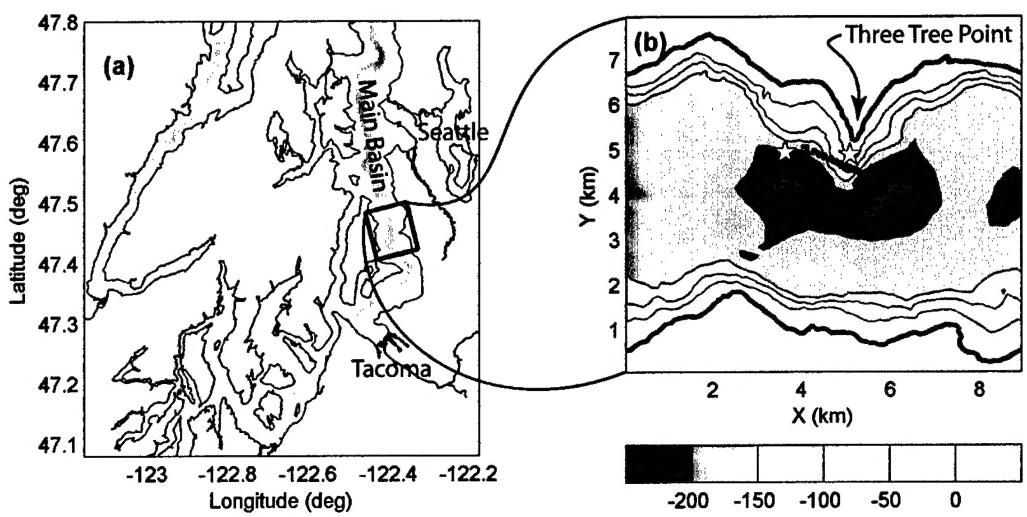


Figure 5: Maps of (a) Puget Sound, Washington, and (b) Three Tree Point (TTP). The spatial domain of the numerical model is depicted in (b); its bathymetry (m) is shown by the grayscale. The line of dots crossing TTP at an angle shows the locations of "Chameleon" microstructure profiler drops.

The primary mechanism by which rough topography influences ocean flows is through "form drag," i.e. the drag due to pressure differences across a topographic feature. This issue was explored through numerical, theoretical, and observational studies. For stratified flow along a rough slope, form drag may be due to either internal wave generation or horizontal flow separation. A parameter predicting these two regimes was determined theoretically [*MacCready and Pawlak*, 2001], and numerical experiments showed that the form drag could be parameterized using a quadratic drag law with O(1) drag coefficient, referenced to the projected frontal area of the topographic obstacle. The form drag was measured observa-

tionally in the tidal flow at TTP. We were able to measure the "internal" part of the form drag (associated with the deformation of isopycnals), and the resulting turbulent dissipation, by collaborating with Jim Moum's group at OSU, who made microstructure measurements Figure 6, at our field site [*Edwards et al.*, 2003]. Both in the observations, and in realistic 3D

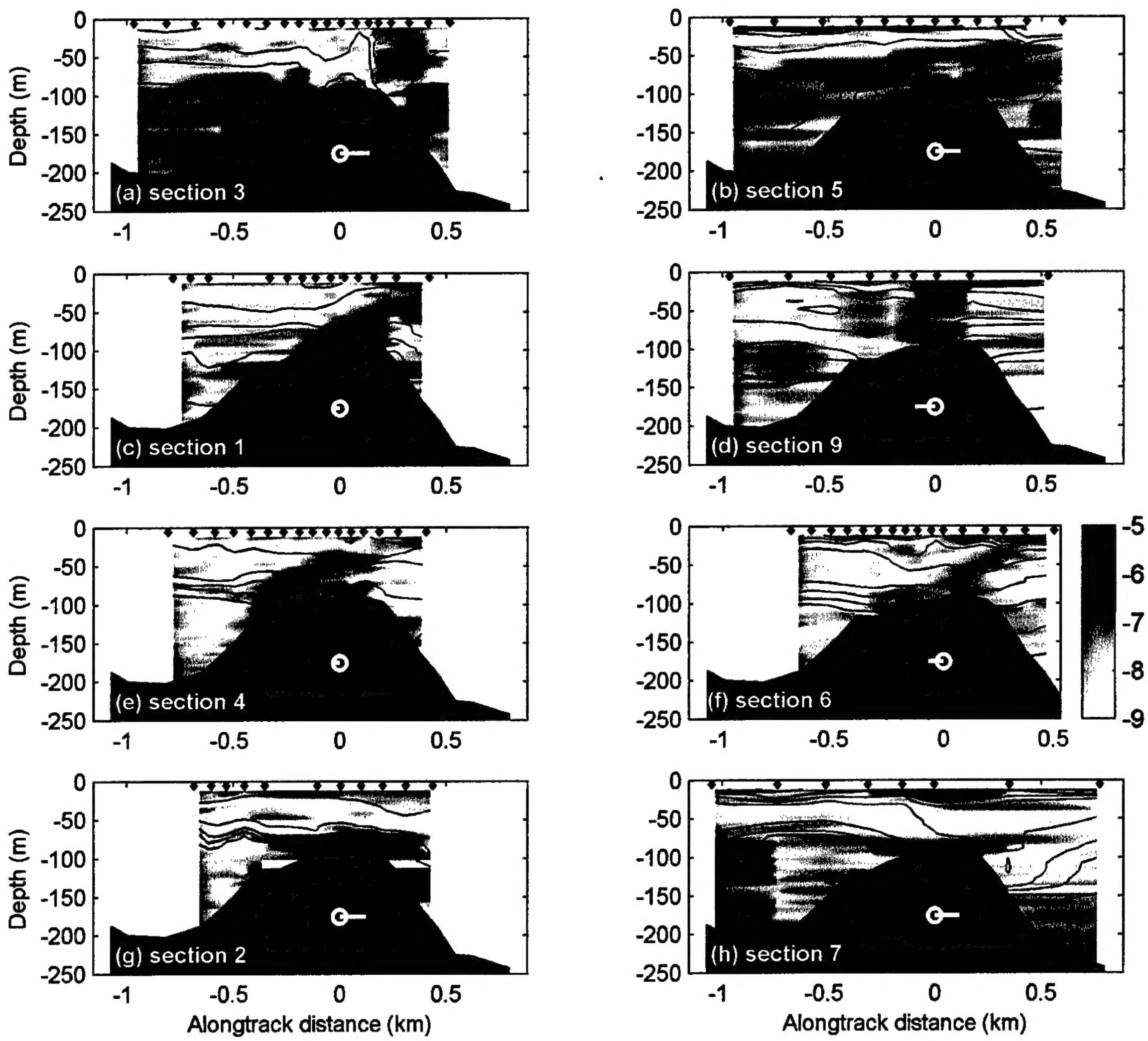


Figure 6: Sections of the $\log_{10}$ of observed turbulent buoyancy flux (color scale), in W kg^{-1}, on eight Chameleon sections across TTP. Potential density contours are overlain. Background tidal currents m s^{-1} are shown as a white line emanating from a circle. The strongest buoyancy flux is near the ridge, or in its lee, during max flood currents, especially in (a).

modeling, the internal form drag on the Point was bigger than the frictional drag by at least a factor of 10, Figure 7, even accounting for the relative frequency of features like TTP in Puget Sound. We were also able to determine the "surface" portion of the form drag at TTP (associated with deformations of the surface height field). MacCready's graduate student, Ryan McCabe, developed a novel technique using drogued drifter tracks to map the surface height field, and thus derive the related form drag. This was found to be comparable in magnitude to the internal form drag. A manuscript on this work is in preparation. Overall, form drag appears to be the dominant mechanism extracting energy from the barotropic tidal flow. A major thrust in MacCready's future work will be: i) to see if form drag is as important in other coastal, estuarine, and slope regions, and (ii) to develop a robust parameterization for that drag. Some if the issues relating to this were discussed in an 2003 'Aha Huliko'a paper.

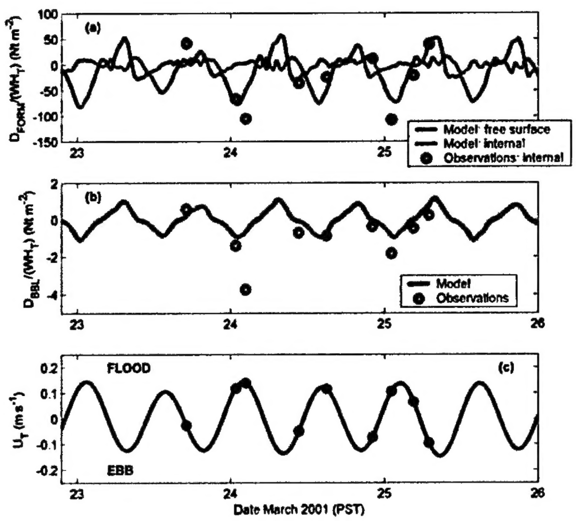


Figure 7: Form drag (a) per unit frontal area, on the Chameleon section, comparing the model results (lines) with values from the 9 Chameleon sections (circles). The frictional drag per unit frontal area is plotted in (b), and the timing of the sections relative to the background tidal velocity is shown in (c).

The dynamics of tidal mixing in channels was explored in a collaboration with the ROMS modeler Robert Hetland (TAMU) and Rocky Geyer (WHOI). Here we explored the idea of using volume integrals between isopycnal surfaces as a natural way of understanding the system-wide effects of tidally-driven turbulent mixing. This was published as MacCready and Geyer (2001) and MacCready et al. (2002). The most interesting result had to do with how the estuarine system built up mixed water during spring tides, and expelled it during

neap tides.

Finally, the SECNAV grant supported an extensive collaboration with Chris Garrett and Richard Dewey (U. Victoria), making observations over a period of 3 years in the Strait of Juan de Fuca. MacCready's student, Wayne Martin, analyzed this data for his Master's project (degree received June 2003, paper in preparation). He found that the large (35 m) vertical excursions of isopycnals in the Strait could be explained as a cross-channel seiche, driven by Ekman transport on the tidal bottom boundary layer. It is likely that this is an important phenomenon in any tidal channel where the cross-channel seiche frequency is comparable to the tidal frequency. Wayne is pursuing a 3D analysis of the system for his PhD.

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